Practitioner's Docket No.: 782_163

PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re the application of: Toshihisa YOKOYAMA, Ken-ichi NODA, Katsuhiro IMAI and Minoru IMAEDA

Ser. No.: 09/854,924 Group Art Unit: 1765

Filed: May 14, 2001 Examiner: Song, M.

Confirmation No.: 7936

For: PROCESS AND APPARATUS FOR PRODUCING AN OXIDE SINGLE CRYSTAL

#14
4/16/03
mw

**RULE 132 DECLARATION OF KATSUHIRO IMAI**

I, Katsuhiro IMAI, hereby declare and state that:

1. I received a Doctor of Science degree in Mineralogy in March, 1993 from the University of Tokyo.

2. I have been employed by NGK Insulators, Ltd., the assignee of the above identified application, since April, 1993. During my employment with NGK, I have been involved with research and development of single crystal materials at the Research Laboratory of NGK Insulators, Ltd., from April, 1993.

3. I have reviewed the prosecution history of the above-identified application, particularly the Final Office Action mailed January 15, 2003 and the Advisory Action mailed March 28, 2003. I have also reviewed Imaeda et al. and Ciszek et al., the applied prior art of record.

4. In the Advisory Action, the Examiner is taking the position that Applicants have not provided evidentiary support for the arguments that: 1) silicon crystals typically have a higher coefficient of thermal conductivity compared to that of oxide single crystals; and 2) silicon crystals typically have a lower coefficient of thermal expansion compared to that of oxide single crystals.

5. With reference to The Chemical Society of Japan (1993): *Kagaku Binran Kisohen* II (Handbook of Chemistry, Fundamental Chemistry Volume II), 4th edition, Maruzen, Tokyo (in Japanese), a data sheet obtained from the INRAD, Inc., website http://www.inrad.com/pdf/Inrad_datasheet_LNB.pdf (a printout of which is attached hereto), oxide single crystals typically have a coefficient of thermal conductivity of 4W/m·K and coefficients of thermal expansion of $14.1 \times 10^{-6}$/K(//a) and $4.1 \times 10^{-6}$/K(//c), whereas silicon crystals typically have a coefficient of thermal conductivity of 148W/mK and a coefficient of thermal expansion of $4.15 \times 10^{-6}$/K. Therefore, those of ordinary skill in the art understand that silicon crystals have a higher coefficient of thermal conductivity and a lower coefficient of thermal expansion in comparison to oxide single crystals.

6. The Imaeda et al. reference relates to oxide single crystals and that reference correctly recognizes that it is undesirable to have too high of a cooling rate after growing the oxide single crystals. Although Imaeda et al. do not specifically address cooling oxide single crystals at the liquid-solid crystal interface, based on the disclosure in Imaeda et al., I would also conclude that one should not use a cooling gas to directly cool the oxide single crystal liquid-solid crystal interface. This is because the temperature at the liquid-solid crystal interface is necessarily higher than the temperature of the grown crystal body, and thus, blowing a cooling gas directly on the oxide single crystal solid-liquid crystal interface

would necessarily produce a greater rate of temperature change at the hotter liquid-solid crystal interface than would be realized if the same cooling medium were blown on the cooler crystal body. Therefore, for the same reasons that it is undesirable to have too high of a temperature gradient in the grown crystal body after crystal growth, as specifically disclosed by Imaeda et al., it is also undesirable to have too high of a temperature gradient at the liquid-solid crystal interface.

7. Ciszek deals with a method of producing a silicon crystal, which includes a step of directing a cooling medium onto the liquid-solid crystal interface portion. Ciszek's method is successful because of the relatively higher coefficient of thermal conductivity and the relatively lower coefficient of thermal expansion compared to those of oxide single crystals (see paragraph 5 above). On the other hand, blowing a cooling medium onto the liquid-solid crystal interface of Imaeda's oxide single crystal would not necessarily produce the benefits disclosed in Ciszek, because of the relatively lower coefficient of thermal conductivity and the relatively higher coefficient of thermal expansion of oxide single crystals. Therefore, skilled artisans would not conclude that oxide single crystals could withstand Ciszek's liquid-solid crystal interface cooling treatment, which, again, is designed for silicon crystals, because oxide single crystals have a lower coefficient of thermal conductivity and a higher coefficient of thermal expansion in comparison to silicon crystals.

8. Based on my academic credentials and work experience, I consider myself to be one of ordinary skill in the art. The claimed invention was not obvious to me at the time it was made. Nor do I believe that the claimed invention would have been obvious to others of ordinary skill in the art absent our discovery.

9. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

April 9, 2003
Date

Katsuhiro Imai

# Lithium Niobate ($LiNbO_3$)

## PHYSICAL PROPERTIES

| | | |
|---|---|---|
| Chemical Formula | | $LiNbO_3$ congruently melting[1] |
| Crystal Symmetry and Class | | trigonal, R3c |
| Point Group | | 3m |
| Lattice Constants[2] | | a = 5.15052(6) Å<br>c = 13.86496(3) Å |
| Density[2] | | 4.640(5) g/cm$^3$ |
| Moh's Hardness | | 5 |
| Fracture Toughness[3] | c-face | 0.67 MPam$^{1/2}$ |
| | x-face | 1.07 MPam$^{1/2}$ |
| | y-face | 1.17 MPam$^{1/2}$ |

Elastic Compliance[4] at Constant Polarization ($S_P$) and at Constant Field ($S_E$) and Temperature Dependence[5]

| (TPa)$^{-1}$ | (TPa)-1 | ($10^{-4}$/°K) |
|---|---|---|
| $S_{P11}$= 4.76 | $S_{E11}$= 5.78 | $(1/S_{E11})dS_{E11}/dT$=1.66 |
| $S_{P12}$= -0.50 | $S_{E12}$= -1.01 | $(1/S_{E12})dS_{E12}/dT$=0.28 |
| $S_{P13}$= -1.20 | $S_{E13}$= -1.47 | $(1/S_{E13})dS_{E13}/dT$=1.94 |
| $S_{P14}$= 1.02 | $S_{E14}$= -1.02 | $(1/S_{E14})dS_{E14}/dT$=1.33 |
| $S_{P33}$= 4.19 | $S_{E33}$= 5.02 | $(1/S_{E22})dS_{E22}/dT$=1.60 |
| $S_{P44}$= 9.3 | $S_{E44}$= 17.0 | $(1/S_{E44})dS_{E44}/dT$=2.05 |
| $S_{P66}$= 10.5 | $S_{E66}$= 13.6 | $(1/S_{E66})dS_{E66}/dT$=1.43 |

Stiffness[4] at Constant Polarization ($C_P$) and at Constant Field ($C_E$) and Temperature Dependence[5]

| (GPa) | (GPa) | ($10^{-4}$/°K) |
|---|---|---|
| $C_{P11}$= 219 | $C_{E11}$= 203 | $(1/C_{E11})dC_{E11}/dT$=-1.74 |
| $C_{P12}$= 37 | $C_{E12}$= 53 | $(1/C_{E12})dC_{E12}/dT$=-2.52 |
| $C_{P13}$= 76 | $C_{E13}$= 75 | $(1/C_{E13})dC_{E13}/dT$=-1.59 |
| $C_{P14}$= -15 | $C_{E14}$= 9 | $(1/C_{E14})dC_{E14}/dT$=-2.14 |
| $C_{P22}$= 252 | $C_{E22}$= 245 | $(1/C_{E22})dC_{E22}/dT$=-1.53 |
| $C_{P44}$= 95 | $C_{E44}$= 60 | $(1/C_{E44})dC_{E44}/dT$= 2.04 |
| $C_{P66}$= 91 | $C_{E66}$= 75 | $(1/C_{E66})dC_{E66}/dT$=-1.43 |

## OPTICAL AND ELECTRO-OPTICAL PROPERTIES

Optical Symmetry — uniaxial negative

Optical Transmission — 0.400 µm - 5.0 µm

Sellmeier Equation Constants[13]

$n = ( A + B/(\lambda^2+C) + D\lambda^2)^{1/2}$ ; $\lambda$ in microns

$n_o$ A=4.9048 B=0.11768 C= -0.0475 D= -0.027169

$n_e$ A=4.582 B=0.099169 C=-0.044432 D= -0.02195

Calculated Refractive Index Values[13]

$n_o$( 1.064 µm) = 2.2322 ; $n_e$( 1.064 µm) = 2.1560

$n_o$( 2.060 µm) = 2.1949 ; $n_e$( 2.060 µm) = 2.1243

$n_o$( 3.500 µm) = 2.1405 ; $n_e$( 3.500 µm) = 2.0788

Photoelastic Strain Coefficients at Constant Field[11]

$\rho_{11}$ = -0.026 $\rho_{31}$ = 0.17

$\rho_{12}$ = 0.08 $\rho_{33}$ = 0.07

$\rho_{13}$ = 0.13 $\rho_{41}$ = -0.151

$\rho_{14}$ = -0.08 $\rho_{44}$ = 0.146

Temperature Variation of Refractive Index[13] for $\lambda$ = 1.0 µm – 4.0 µm

$dn_o/dT = 3.3 \times 10^{-5}$ /°C

$dn_e/dT = 37 \times 10^{-5}$ /°C

Nonlinear d Coefficients[12,20]

$d_{22}$ = 2.4 pm/V

$d_{31}$ = -4.52 pm/V

$d_{33}$ = 31.5 pm/V

Effective Nonlinear Optical Coefficient

$d_{eff} = d_{31} \sin\theta - d_{22} \cos\theta \sin 3\Phi$

Electro Optic Coefficients @ 0.633 µm[23]

$r_{13}^T$ = 10 pm/V $r_{13}^S$ = 8.6 pm/V

$r_{22}^T$ = 6.8 pm/V $r_{22}^S$ = 3.4 pm/V

$r_{33}^T$ = 32.2 pm/V $r_{33}^S$ = 30.8 pm/V

$r_{51}^T$ = 32 pm/V $r_{51}^S$ = 28 pm/V

Variation of Electro Optic Coefficient $r_{22}$ with Wavelength[22]
And Calculated Half-wave Voltage For 9mmx9mmx25mm Q-Switch

$V_{1/4} = \lambda d / ( 4 n^3 l r_{22})$

| $r_{22}^T$ | $V_{1/4}$ |
|---|---|
| 1.064 µm = 5.6 pm/V | 1.55 kVolts |
| 1.318 µm = 5.4 pm/V | 2.02 kVolts |
| 1.55 µm = 5.3 pm/V | 2.44 kVolts |
| 2.10 µm = 5.2 pm/V | 3.45 kVolts |
| 2.79 µm = 5.1 pm/V | 4.78 kVolts |
| 2.94 µm = 5.1 pm/V | 5.08 kVolts |

Damage Threshold[2] — 3 J/cm$^2$ @ 10 nsec

## THERMAL AND ELECTRICAL PROPERTIES

| | |
|---|---|
| Melting Point[7] | 1240° C |
| Curie Temperature[8] | 1145° C |
| Thermal Conductivity[9] | 4. W/m°K |
| Thermal diffusivity[6] | $9 \times 10^{-7}$ $m^2$/sec |
| Specific Heat[9] | 0.633 J/g°K |
| Thermal Expansion[10] | $\alpha_a = 14.1 \times 10^{-6}$/°K<br>$\alpha_c = 4.1 \times 10^{-6}$/°K |
| Resistivity[14] | $2 \times 10^{30}$ Ω - cm @ 200° C |

Dielectric Constants[15]

$K_{11}^S = 43$ $K_{11}^T = 78$
$K_{33}^S = 28$ $K_{33}^T = 32$

Loss tangent[15] @400 °C

x-axis Tanδ =0.0006
y-axis Tanδ =0.001

## Typical Polish Specifications

| | |
|---|---|
| Wavefront Distortion: | λ / 8 @ 633 nm |
| Flatness: | λ / 10 @ 633 nm |
| Parallelism: | 1 arcseconds |
| Scratch - Dig: | 10 - 5 |

# INRAD Lithium Niobate

## Description

Lithium niobate is a ferroelectric material suitable for a variety of applications. Its versatility is made possible by the excellent electro-optic, nonlinear, and piezoelectric properties of the intrinsic material. It is one of the most thoroughly characterized electro-optic materials, and crystal growing techniques consistently produce large crystals of high perfection.

Applications that utilize the large electro-optic coefficients of lithium niobate are optical modulation and Q-switching of infrared wavelengths. Because the crystal is nonhygroscopic and has a low half-wave voltage, it is often the material of choice for Q-switches in military applications. The crystal can be operated in a Q-switch configuration with zero residual birefringence and with an electric field that is transverse to the direction of light propagation. Because piezoelectric ringing can be severe, piezoelectrically damped designs can be very useful. The damage threshold of the intrinsic material at 1.06 microns with a 10 nsec pulse is approximately 3 J/cm$^2$. With appropriate AR coatings, a surface damage threshold of 300-500 MW/cm$^2$ can be achieved for the same conditions.

Applications that use the large nonlinear d coefficient of $LiNbO_3$ include optical parametric oscillaton, difference frequency mixing to generate tunable infrared wavelengths, and second harmonic generation. With a broad spectral transmission, which ranges from 0.4 µm to 5.0 µm with an $OH^-$ absorption at 2.87 µm, a large negative birefringence, and a large nonlinear coefficient, phasematching is an effective way to generate tunable wavelengths over a broad wavelength range.

Lithium niobate is particularly effective for second harmonic generation of low power laser diodes in the 1.3 to 1.55 µm range.

For infrared generation by difference frequency mixing, the peak power limit is considerably lower than for 1.064 µm, being about 40 MW/cm$^2$. Efficiencies for difference frequency mixing generally are smaller than shg efficiencies with KDP or BBO, which is due to the lower peak powers that can be tolerated by the crystal and the fact that the longer wavelength photons that are generated in the process are less energetic. Typical powers for 10 nanosecond long pulses with 5 mm diameter beams are 30 mJ/pulse of 0.640 µm minus 40 mJ/pulse of 1.064 µm to produce 2.5 mJ/pulse at 1.54 µm, and 32 mJ/pulse of 0.532 µm minus 32 mJ/pulse of 0.640 µm to produce 0.25 mJ/pulse at 3.42 µm.

INRAD offers lithium niobate in a variety of configurations. Standard cuts are available as OPO crystals, Q-switches, difference frequency mixing crystals, autocorrelation crystals, and optical waveguide wafers.

Please consult an INRAD sales engineer for assistance in crystal selection and packaging.

At INRAD, all crystal growth, orientation, fabrication, polishing, and testing of $LiNbO_3$ is done at one site so that you are assured of complete traceability and satisfaction with every crystal that you purchase.

## References


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## 5・2　膨張率と圧縮率

### 5・2・1　固体単体の線膨張率および体膨張率

セルシウス温度が0℃および$\theta$における長さおよび体積を，それぞれ$l_0$, $v_0$および$l$, $v$とすれば，一般に線膨張率$\beta$および体膨張率$\alpha$はそれぞれ

$$\beta=\frac{1}{l_0}\frac{dl}{d\theta} \qquad (5\cdot1)$$

$$\alpha=\frac{1}{v_0}\frac{dv}{d\theta} \qquad (5\cdot2)$$

で与えられる．

温度$\theta_1$および$\theta_2$における値をそれぞれ$l_1$, $v_1$および$l_2$, $v_2$とすれば，$\theta_1$と$\theta_2$との間の平均線膨張率$\beta_m$および平均体膨張率$\alpha_m$はそれぞれ

$$\beta_m=\frac{1}{l_0}\frac{l_2-l_1}{\theta_2-\theta_1} \qquad (5\cdot3)$$

$$\alpha_m=\frac{1}{v_0}\frac{v_2-v_1}{\theta_2-\theta_1} \qquad (5\cdot4)$$

で与えられる．さらに精密な目的に対しては

$$l=l_0(1+\beta_1\theta+\beta_2\theta^2+\beta_3\theta^3) \qquad (5\cdot5)$$

$$v=v_0(1+\alpha_1\theta+\alpha_2\theta^2+\alpha_3\theta^3) \qquad (5\cdot6)$$

で表わされる．なお等方性の物質では$\alpha=3\beta$である．

表 5・29　固体単体の線膨張率$\beta$[1]

| 物質 | | $\theta$/℃ | $\beta$または$\beta_m$/$10^{-6}K^{-1}$ | 物質 | | $\theta$/℃ | $\beta$または$\beta_m$/$10^{-6}K^{-1}$ | 物質 | | $\theta$/℃ | $\beta$または$\beta_m$/$10^{-6}K^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ag | | −250〜0 | 0.170 | Fe | | 0〜898 | 0.1276 | Pd | | 0〜100 | 0.106 |
| | | 0〜100 | 0.193 | | 〃 | 816〜932 | 0.128 | Pt | | 0〜100 | 0.0899 |
| Al | | −190〜0 | 0.180 | Ga | | −72.3〜18 | 0.53 | | | 0〜900 | 0.0994 |
| | | 0〜100 | 0.237 | Ge | | 0〜400 | 0.077 | Rb | | 20 | 0.963 |
| | | 20〜300 | 0.258 | Hg | β軸 | −182〜−79[2] | 0.490 | Rh | | 12〜20 | 0.085 |
| As | β軸 | 6 | 0.48 | | α軸 | 〃 | 0.370 | | | 0〜50 | 0.196 |
| | α軸 | 6 | 0.09 | I | | −80〜25 | 2.20[2] | Ru | | 18〜32 | 0.0975 |
| Au | | −190〜0 | 0.131 | In | | 0〜100 | 0.56 | S | | −223〜−185 | 0.71[2] |
| | | 0〜100 | 0.142 | Ir | | 0〜100 | 0.0653 | | | −185〜−79 | 1.50[2] |
| Be | | 20 | 0.15 | K | | 0〜50 | 0.83 | | | −79〜18 | 3.20[2] |
| Bi | β軸 | 20〜240 | 0.102 | La | | 0〜300 | 0.065 | | | (mp)[2] | 350[2] |
| | α軸 | 20〜240 | 0.128 | Li | | 0〜95 | 0.56 | Sb | β軸 | 20〜100 | 0.1717 |
| Br | | −273〜−194 | 2.00[1] | Mg | β軸 | 16〜35 | 0.271 | | α軸 | 〃 | 0.090 |
| C | ダイヤモンド | 0〜70 | 0.0122 | | α軸 | 〃 | 0.243 | Si | | 10〜50 | 0.0415 |
| | 黒鉛 | 20〜40 | 0.06965 | Mn | α体 | −20〜0 | 0.2163 | Se | β軸 | 0〜20 | 0.5809 |
| | a軸 | 1 000〜1 600 | 0.0095 | Mo | | 0〜100 | 0.051 | | α軸 | 0〜20 | 0.1583 |
| | c軸 | 1 050〜1 640 | 0.2800 | Na | | 0 | 0.686 | Ta | 焼なまし | 約 20〜100[2] | 0.665 |
| Cd | β軸 | 20〜100 | 0.526 | | | 0〜100 | 0.71 | | 焼なまし | 〃 | 0.667 |
| | α軸 | 〃 | 0.214 | | | −97.6 | 2.78[2] | Te | β軸 | −20 | −0.0016 |
| Co | | 20〜100 | 0.126 | Ni | | 0〜100 | 0.125 | | α軸 | 〃 | 0.272 |
| | | 100〜200 | 0.136 | | | 300〜600 | 0.165 | Tl | 〃 | 0〜100 | 0.294 |
| Cr | | 0〜100 | 0.084 | | | 600〜900 | 0.178 | | | 100〜200 | 0.306 |
| Cs | | −20 | 0.97 | Os | | 0〜100 | 0.070 | W | | 0〜100 | 0.045 |
| | | −185〜−103 | 0.121 | P | | −79〜19 | 3.75[2] | Zn | β軸 | 20〜250 | 0.530 |
| Cu | | −103〜0 | 0.154 | | | 24〜50 | 5.60[2] | | α軸 | 〃 | 0.160 |
| | | 0〜101 | 0.162 | Pb | | 0〜100 | 0.290 | Zr | | −20〜0 | 0.0563 |
| | | 300 | 0.175 | | | 20〜300 | 0.313[2] | | | 0〜100 | 0.0437[1] |

1) "Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik", 6 Aufl., II Band, 1 Teil, S. 378〜448, Springer-Verlag (1971).

＊1　体膨張率$\alpha$または$\alpha_m$をあらわす．

＊2　融点

### 5・2・2　化合物の線膨張率および体膨張率[1]

表 5・30　固体化合物の線膨張率$\alpha$ならびに膨張率$\beta$ (1)

| 化合物 | $\theta$/℃ | $\alpha$または$\alpha_m$/$10^{-6}K^{-1}$ | 化合物 | $\theta$/℃ | $\alpha$または$\alpha_m$/$10^{-6}K^{-1}$ | 化合物 | $\theta$/℃ | $\alpha$または$\alpha_m$/$10^{-6}K^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| 無機質化合物 | | | $H_2O$(氷) | −73 | 9.576[2] | KI | −79〜0 | 1.25 |
| AgCl | 20〜250 | 1.03 | | 0 | 0.558[2] | $KMnO_4$ | −78〜18 | 2.20 |
| $Al_2O_3$ | 20〜800 | 0.000 | $H_2SO_4 \cdot H_2O$ | −78〜0 | 2.20 | $KNO_3$ | −78〜18 | 2.10 |
| BaCl | 20〜150 | 0.50 | KBr | −79〜0 | 1.10 | KOH | 30〜120 | 1.95 |
| CaCl | 20〜150 | 0.87 | KCl | −78〜25 | 1.01 | $K_2SO_4$ | −78〜21 | 1.30 |
| CaO | 30〜75 | 0.21[2] | $KClO_3$ | −78〜21 | 2.20 | MgO | 30〜75 | 0.139[2] |

＊　線膨張率$\beta$または$\beta_m$をあらわす．

1) "Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik", 6 Aufl., II Band, 1 Teil, S. 469〜778, Springer-Verlag (1971).

表 6・03 固体単体の熱伝導率 $\lambda$/W m$^{-1}$ K$^{-1}$

| 固体 | 温度 T/K | | | | | | |
|---|---|---|---|---|---|---|---|
| | 50 | 100 | 200 | 300 | 400 | 700 | 1000 |
| 銀 | 700 | 450 | 430 | 427 | 420 | 397 | 374 |
| Au | 420 | 325 | 327 | 315 | 312 | 298 | 278 |
| B | 404 | 190 | 52.5 | 27.6 | 13.7 | 0.41 | 0.29 |
| Be | 4000 | 990 | 301 | 200 | 161 | 115 | 89.7 |
| Bi (⊥c) | 30.7 | 15.8 | 11.3 | 9.15 | 8.22 | (14.2) | (16.8) |
| C(黒鉛) | 2680 | 2 010 | 1 430 | 900 | 632 | | |
| C(ダイヤ) | 9200 | 10 000 | 4 040 | 2 310 | 1 550 | | |
| C(非晶) | 3900 | 3 450 | 2 260 | 1 350 | 956 | | |
| C(黒鉛⊥) | 17 | 58 | 120 | 129 | 118 | 65 | 64 |
| C(黒鉛∥) | 19 | 42 | 86 | 98 | 90 | 65 | 69 |
| C(Pyr⊥c) | 2300 | 4 980 | 3 250 | 1 600 | 1 480 | 790 | 520 |
| C(Pyr∥c) | 103 | 39 | 15 | 9.5 | 7.0 | 3.8 | 2.5 |
| Ca | 120 | 103 | 99.3 | 98.8 | 94.7 | (49.0) | |
| Ce | 3.79 | 6.00 | 5.00 | 11.4 | 13.3 | 10.0 | 21.6 |
| Co | 298 | 168 | 122 | 99.3 | 84.8 | | |
| Cr | 317 | 136 | 111 | 80.3 | 67.3 | 73.7 | 65.3 |
| Cs | 44.7 | 35.7 | 36.8 | 35.9 | (20.3) | (20.1) | (17.5) |
| Cu | 13.5 | 10.5 | 9.59 | 10.7 | 10.9 | 12.8 | 15.2 |
| Dy | 9.28 | 11.9 | 14.3 | 14.3 | 13.9 | 16.5 | 18.8 |
| Er | 372 | 132 | 86 | 80.3 | 69.4 | 48.7 | 32.5 |
| Eu(⊥c) | 63.6 | 67.4 | 42.4 | 40.5 | (27.0) | | |
| Fe | 19.0 | 11.5 | 9.98 | 9.28 | 10.1 | | |
| Ga | 615 | 232 | 96.8 | 29.9 | 43.2 | 22.5 | 17.4 |
| Gd | 26.3 | 25.0 | 34.4 | 53.0 | 33.5 | 21.0 | 26.7 |
| Ge | 35.4 | 32.0 | 28.0 | (9.94) | (9.84) | (12.7) | (21.7) |
| Hf | 7.77 | 7.62 | 13.0 | 13.0 | 13.4 | | |
| He | | | | 0.149 | (0.114) | (0.053) | |
| Ho | 104 | 97.6 | 89.7 | 81.7 | 74.5 | 41.4 | 52.4 |
| In | 472 | 172 | 153 | 147 | 146 | 135 | 126 |
| Ir | 112 | 107 | 104 | 102 | (52.0) | (40.6) | (51.3) |
| K | 0.42 | 0.78 | 1.18 | 1.36 | 1.46 | 1.26 | 0.89 |
| La | 235 | 116 | 88.1 | 76.5 | 72.1 | (50.9) | (60.0) |
| Lu | 20.9 | 18.9 | 17.2 | 16.2 | | | |
| Mg | 375 | 169 | 159 | 156 | 153 | 147 | (81) |
| Mn | 1.05 | 5.79 | 7.17 | 7.82 | | | |

| 固体 | 温度 T/K | | | | | | |
|---|---|---|---|---|---|---|---|
| | 50 | 100 | 200 | 300 | 400 | 700 | 1000 |
| Mo | 300 | 178 | 143 | 138 | 134 | 123 | 112 |
| Na | 156 | 132 | 138 | 132 | (85.5) | (71.5) | (58.8) |
| Nb | 76 | 55.2 | 52.8 | 53.7 | 55.2 | 55.8 | 64.4 |
| Nd | | | 16.6 | 16.5 | 16.8 | 18.1 | 21.5 |
| Ni | 336 | 158 | 105 | 90.5 | 80.1 | 65.5 | 71.8 |
| Os | 265 | 112 | 90.8 | 87.6 | 86.9 | | 86.8 |
| P(赤) | 42.7 | 30.7 | 17.7 | 12.1 | | | |
| Pb | 43.5 | 38.6 | 36.6 | 35.2 | 33.8 | (17.0) | (21.5) |
| Pd | 128 | 77.3 | 76.5 | 75.5 | 76.5 | 75.5 | 75.9 |
| Pr | | 7.69 | 10.6 | 12.5 | 13.6 | 16.3 | 21.6 |
| Pt | 82.7 | 80.3 | 72.9 | 68.2 | (39.1) | (28.9) | (25.7) |
| Re | 96.2 | 58.9 | 51.0 | 47.9 | 46.1 | 44.0 | 44.6 |
| Rh | 570 | 186 | 154 | 150 | 146 | 131 | 121 |
| Ru | 498 | 154 | 118 | 117 | 115 | | |
| S | 0.277 | 0.205 | 0.255 | 0.269 | (0.132) | | |
| Sb | 59.3 | 41.4 | 30.2 | 24.3 | 21.8 | 17.4 | (27.0) |
| Sc | 13.5 | 14.9 | 15.3 | 15.8 | | | |
| Se(⊥c) | 80.0 | 16.8 | 0.08 | 6.32 | 5.36 | | |
| Si | 2680 | 884 | 298 | 148 | 98.9 | 50.8 | 31.2 |
| Sm | 7.52 | 7.35 | 11.7 | 12.8 | 13.3 | | |
| Sn | 113 | 85 | 73.2 | 66.6 | 62.2 | (34.2) | (40.5) |
| Ta | 72 | 58.2 | 57.5 | 57.3 | 57.8 | 59 | 60.2 |
| Tb | 14.7 | 11 | 9.98 | 10.( | | | |
| Te(⊥c) | 45.4 | 25.9 | 8.16 | 3.95 | 2.94 | 2.20 | |
| Th | 58.2 | 45.8 | 40.6 | 49.1 | 45.8 | 50.4 | 51.5 |
| Ti | 40.1 | 31.8 | 24.5 | 21.9 | 20.1 | 19.4 | 20.7 |
| Tl | 62.8 | 56.6 | 48.4 | 46.1 | 45.8 | | |
| Tm | 10.3 | 13.5 | 16.2 | 16.8 | | | |
| U | 18.9 | 21.7 | 25.1 | 27.6 | 29.6 | 36.8 | 43.9 |
| V | 48.5 | 35.7 | 31.5 | 31.5 | 32.1 | 35.8 | 38.6 |
| Y | 16.8 | 13.7 | 15.6 | 16.2 | 16.9 | 20.3 | 23.5 |
| Yb | | | 28.4 | 34.5 | 34.1 | | |
| Zn | 278 | 124 | 123 | 121 | 116 | (69.0) | (67.2) |
| Zr | 29.7 | 24.2 | 23.2 | 22.7 | 21.6 | 20.8 | 23.7 |

1 表中の( )を付けた数値は最新資料の値である。

2 物質名に付けた ⊥c, ∥c などは、単結晶試料の c 軸に垂直, c 軸に平行などを示す。ただし、C(黒鉛)については、ATJ 型の加熱圧形時の圧縮方向に対する垂直 (⊥), 平行 (∥) を示し、C(Pyr.) は熱分解黒鉛を示す。

表 6・04 ガラスと酸化物の熱伝導率 k/W m$^{-1}$K$^{-1}$

| 固体 | 温度 T/K | | | | | | |
|---|---|---|---|---|---|---|---|
| | 100 | 200 | 300 | 400 | 500 | 700 | 1000 |
| ガラス | | | | | | | |
| $SiO_2$ | 0.69 | 1.14 | 1.38 | 1.51 | 1.62 | 1.92 | 2.57 |
| ガラス | | | | | | | |
| Pyrex 7740[1] | 0.58 | 0.90 | 1.10 | 1.24 | 1.36 | 1.65 | |
| ロセラム | | | | | | | |
| 9608)[2] | 5.42 | 4.74 | 3.99 | 3.65 | 3.45 | 3.19 | 2.97 |
| | | | | | | | |
| サファイア) | 450 | 92 | 40 | 32.4 | 24.2 | 13.4 | 10.5 |
| 結晶) | 138 | 55 | 36 | 26.4 | 20.2 | 12.6 | 7.9 |
| | | 424 | 378 | 196 | 146 | 87 | 67 |

| 固体 | 温度 T/K | | | | | | |
|---|---|---|---|---|---|---|---|
| | 100 | 200 | 300 | 400 | 500 | 700 | 1000 |
| MgO | 270 | 94 | 60 | 43.1 | 32 | | |
| $SiO_2$ | | | | | | | |
| (石英⊥c 軸) | 39 | 16.4 | 10.4 | 7.6 | 6.0 | 4.5 | |
| (石英∥c 軸) | 20.8 | 8.5 | 6.2 | 4.7 | 3.8 | 3.1 | |
| $ThO_2$ | | | 12.2 | 10.2 | 8.1 | 5.5 | 3.7 |
| $TiO_2$ | | | | | | | |
| (ルチル⊥c 軸) | 23.5 | 13.7 | 10.4 | 8.5 | | | |
| (ルチル∥c 軸) | 16.9 | 9.7 | 7.4 | 6.0 | | | |
| (多結晶) | | | 8.4 | 7.0 | 5.9 | 4.4 | 3.5 |
| $UO_2$ | 8.0 | 8.6 | 8.2 | 7.4 | 6.5 | 5.1 | 3.8 |

Corning 社製, $\rho$=2.226 g cm$^{-3}$

Corning 社製, $\rho$=2.601 g cm$^{-3}$